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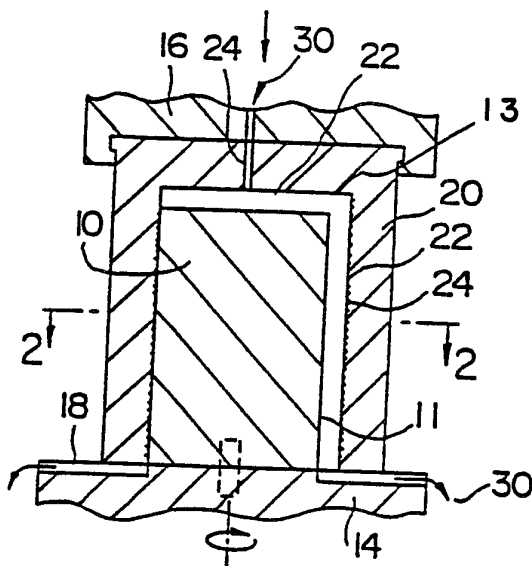
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(54) Title: ORBITAL CHEMICAL MILLING



(57) Abstract

A method for chemical milling a workpiece (10) utilizing a chemical milling fluid that is passivating to the workpiece, wherein the tool (20) is provided with an abrasive surface (22), and the tool and workpiece are brought together with a contacting relative motion so that the abrasive surface will selectively abrade the workpiece to remove any passivation layer therefrom in those areas to be machined and such that the unabraded surface areas will retain the passivation layer to prevent chemical milling thereof, and a reciprocal motion between the tool and workpiece is also effected to pump the chemical milling fluid through the gap between the tool and workpiece and prevent reduction of the milling rate of the milling fluid.

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ORBITAL CHEMICAL MILLING**BACKGROUND OF THE INVENTION****1. Field of the Invention:**

5 This invention relates generally to a new and unique chemical milling process, and more specifically to a unique machining process which has greatly improved shaping capabilities over comparable prior art techniques by including a relative contacting movement, orbital or
10 otherwise, between the tool and workpiece in one plane, and further effecting a reciprocating motion as a result of the orbital motion or by a separate reciprocal motion in a second plane. This new and inventive process greatly expands the capabilities of chemical milling to make
15 possible the machining of complex external or internal shapes with a high degree of accuracy and precision not obtainable by prior art chemical milling practices. Of particular significance is the fact that the process of this invention provides a relatively simple method of
20 machining such complex shapes as turbine blades with a high degree of accuracy, either individually, or even a whole circular array of turbine blades on a complex turbine wheel simultaneously.

2. The Prior Art:

25 Chemical milling is one of the non-traditional machining processes, which is in essence an application of a chemical reaction in a machining process to selectively and controllably remove metal from a workpiece. Chemical milling is ideally suited to the machining of metals which
30 are difficult to machine by the more traditional machining

processes, and does not induce any residual stresses or distortion in the machined workpiece. Even heat treated and work hardened metals can be machined by chemical milling without any adverse effects on the metal's pre-
5 machining properties.

Unlike conventional machining, chemical milling has no tool to contact the workpiece, and accordingly, removes metal from a workpiece chemically atom by atom with virtually no tool wear.

10 At the same time, the reaction products formed between the milling fluid and the workpiece are often left deposited on the surface of the workpiece. Such deposits form a film of "passivated" material which impede or block the chemical milling reaction.

15 It is usual to adopt conditions and chemical milling fluids which minimize the formation of a passivation layer on the workpiece to avoid the delays involved by the reduced machining rate which results. When excessive passivation occurs, it must be removed from the milling
20 operation to continue.

The usual adaptations tend, as a general rule, to require a less-than-maximum machining rate as the necessary expedient to avoid excessive or unmanageable passivation.

25 In such systems, the chemical milling procedure employs masking to protect areas where milling action is not desired, making appropriate allowances for undercutting of the edges of the mask.

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In one variation on the general theme, Taylor; U.S. Patent 3,593,410, employs a chemical solution to react with the surface of a die member to form a reaction product to a depth of a few ten-thousandths of an inch on the surface. The reaction product is then ground away by vibrational relative motion between the surface and an abrasive coated matching member to "spot" the die surface. In the Taylor procedure, the die must be formed in very close conformity to the required shape before the "spotting" procedure is employed; Taylor does not contemplate a milling procedure to achieve the required shape and dimensions.

SUMMARY OF THE INVENTION

This invention is predicated on the development of a new and unique method of chemical milling which has the capability of machining complex two and three dimensional configurations with a high degree of accuracy, precision, and resolution of intricate detail. In this unique new chemical milling process, the tool is similar to the tool used in orbital grinding, in that it has a body with abrasive particles at the surface such that the particles will abrade surfaces of the workpiece. In this process, the tool is not a rotating tool, and can therefore have any surface configuration desired to be machined into the workpiece, including three dimensional configurations. In the new chemical milling process of this invention, the tool and workpiece are brought together under chemical milling processing conditions with relative motion between the two components, while at the same time, the surface

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areas of contact reciprocate through a cycle whereby they are in contacting motion for a moment of time, then move away from each other and then back into contacting motion to essentially "pump" the chemical milling fluid through the interfaces. Depending upon the geometry of the interfaces, the relative motion alone can effect the reciprocating pumping action, or if needed, a second relative motion in a different plane can be imposed to effect the reciprocating relative motion. While the contacting motion will normally be a circular orbital motion, it can be any two dimensional reciprocating movement describable by a point on the moving component moving in a closed trajectory line in a plane transverse to that of the feed axis, and may define many forms such as circular, oval, elliptical, polygonal, and other forms, including combinations thereof, as may be essential to achieve the machining desired. The reciprocating relative motion between the contacting interfaces will cause spent chemical milling fluid to be purged from the interface while drawing in fresh chemical milling fluid with each cycle of reciprocation motion. As in more conventional applications, the tool and/or workpiece may have to be made to progressively advance one toward the other at a feed rate in proportion to the metal removal rate to maintain a preferred gap spacing between the tool and workpiece as the metal is being removed.

The chemical milling fluid used in this inventive process will be passivating and may be very strongly passivating to the workpiece, which serves to provide both

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a macro and micro controllability to the inventive process, as described herein below.

The tool utilized in this inventive process must be provided with abrasive particles extending from a body portion. During the process, the abrasive particles extending from the tool surface must be in contact against the surface of the workpiece sufficient only to lightly abrade the workpiece surface in a manner akin to orbital machining, but serving only to abrade away the passivation layer. At the same time, and/or a brief period, as brief as a fraction of a second thereafter, the chemical milling fluid will chemically mill the workpiece surface until passivation again occurs. Unlike conventional grinding, the physical abrasion caused by the orbital action between the tool and workpiece in this invention does not significantly contribute to the machining of the workpiece, but is sufficient only to abrade away the passivation layer, as above noted. This rather limited abrasive action will, however, provide numerous unexpected advantages which will add a considerable measure of control to the chemical milling metal removing action, and enhance the capabilities of the process to greatly improve precision and resolution of detail.

In accordance with the basic application of this invention, the machining is achieved almost entirely by the chemical milling action. The chemical milling fluid and operating parameters are normally selected so that the fluid is very strongly passivating to the workpiece, particularly at the finish of the machining operation to

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achieve a greater degree of precision. The orbital abrading action of the tool surface serves merely to lightly abrade the surface of the workpiece, sufficient only to remove or prevent the formation of the passivation layer in those selected areas where the tool abrades the workpiece. The passivating nature of the chemical milling fluid serves not only to prevent the chemical milling action on those surfaces where the tool, by design, does not abrade away the passivation layer, but further serves, in combination with proper tool design and motion thereof, to control the metal removal on those surfaces where the tool does remove the passivation layer. Accordingly, the chemical milling machining will progress only on those areas where the tool has removed, or prevented the formation of, the passivation layer, and then only to the extent as determined by the tool design and motion thereof. The tool geometry, nature of the abrasive surface thereon and its motion relative to the workpiece, can be utilized to very carefully define those areas where the chemical milling machining is to be effected and the degree of chemical milling machining on those various surfaces, to thereby control and regulate the overall chemical milling process to a far greater degree than had been capable by prior art practices.

In addition to the above advantages of this invention, numerous other unexpected advantages are afforded by this inventive process. For example, the process of this invention will tend to significantly minimize overcut because only those surfaces abraded by

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the tool will be chemical milling machined. In addition, because there is no need to adjust conditions for preventing passivation, there is a wider choice of chemical milling fluids and accordingly fluids can be used which will minimize stray etching. Still another beneficial factor is that the process of this invention can be performed at high metal removal. Stray etching and undercutting are prevented from occurring in the process of this invention by an intentionally formed passivation layer, so that very sharp external corners can be formed even at high metal removal rates. It is difficult to machine sharp external corners by conventional chemical milling, as stray etching will erode at least a portion of the workpiece surface around the corner from the surface to be milled, thereby tending to "round" the corner. Sharp external corners can readily be machined by the process of this invention, however, by utilizing proper tool design which will permit quick passivation on one surface while machining an adjacent surface to effect a sharp corner as desired. In view of these and other considerations, this new and unique process for chemical milling machining will provide a significantly greater degree of control of the overall machining action to produce a much greater degree of accuracy and precision in both simple and complex surfaces and images than has been possible with any prior art chemical milling machining process.

In addition to the above considerations, the process of this invention finds particular utility in the

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that utilizes a strongly passivating fluid and incorporates a light oscillating or orbital abrading action by the tool to selectively and controllably remove the passivation layer and thereby selectively control the
5 chemical milling machining action.

It is a further object of this invention to provide a new and improved method for chemical milling machining which utilizes a reciprocal motion between the tool and workpiece to pump and enhance the circulation of the
10 chemical milling fluid through the interface to thereby permit the use of higher removal rates and to improve the quality of the finished product.

It is still another object of this invention to provide a new and improved method for chemical milling
15 machining which permits a wider selection of chemical milling fluids and thus permits the use of those chemical milling fluids that will minimize stray etching.

It is an even further object of this invention to provide a new and improved method for chemical milling
20 machining which eliminates or minimizes overcutting.

It is another object of this invention to provide a process machining complex shapes such as turbine blades, either individually or in groups, including the simultaneous machining of all turbine blades on a one
25 piece turbine wheel.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a schematic cross-sectional elevational view illustrating a very simple embodiment of this

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invention utilizing only a simple orbital relative motion to machine a simple cylindrical workpiece.

Figure 2 is a schematic cross-sectional plan view of the embodiment illustrated in Figure 1.

5 Figure 3 is a schematic cross-sectional elevational view illustrating another very simple embodiment of this invention utilizing a combination of an orbital relative motion and a reciprocal relative motion to machine a flat surface on a workpiece, showing the tool and workpiece in
10 contact.

Figure 4 is identical to Figure 3 except that it shows the tool and workpiece in a non-contacting relationship.

Figure 5 is a schematic cross-sectional elevational
15 view illustrating an embodiment of this invention for machining a flat surface utilizing an orbital motion inclined to the plane of the workpiece surface, showing the tool and workpiece in contact.

Figure 6 is a schematic cross-sectional elevation the
20 same as that of Figure 5 but illustrating the tool rotated through one-half of cycle so that it is not in contact with the workpiece.

Figure 7, is a schematic cross-sectional elevational view of a casting, on an unworked workpiece.

25 Figure 8 is a schematic cross-sectional elevational view of the workpiece of Figure 7 being machined in accordance with one embodiment of this invention to produce several faces therein.

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Figures 9a, 9b, and 9c are isometric views of a turbine blade showing three stages in the process of repairing a crack therein.

Figure 10 is a schematic isometric view illustrating the application of the process of this invention in finishing the turbine blade illustrated in Figure 9c.

Figure 11 is a cross-sectional end view of the tool and workpiece during the finishing operation schematically illustrated in Figure 10.

Figure 12 is a schematic isometric view of a tool as placed on a turbine wheel to machining all of the turbine blades in a given circle of the turbine wheel.

DETAILED DESCRIPTION OF THE INVENTION

Throughout the description of the invention, the term "relative" contacting motion or "relative" orbital motion or movement between the contacting surfaces of the workpiece and tool is used to indicate that either or both the workpiece and tool may be in motion to effect a working of the workpiece, with the tool lightly abrading the surface of the workpiece. The actual relative contacting motion at the interface between the workpiece and tool and may or may not be orbital, depending on the geometry of the workpiece surface. In addition to the essential "relative" contacting motion, there must also be a relative reciprocating motion where at least portions of the contacting interfaces between the tool and workpiece oscillation to move into contact and away from contact, for purposes of pumping the chemical milling fluid. Here again relative reciprocating motion is meant to indicate

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that either or both the workpiece and tool may be in motion to effect a resultant reciprocating movement which may be a specific reciprocating movement in addition to the relative contacting motion in a different plane, or it
5 may be a natural resultant reciprocating motion at the contacting interface created by a relative contacting orbital motion.

In addition to the above noted motion or motions, whether effected by a single contacting orbital motion or
10 the combination of a contacting relative motion and a reciprocating motion, a feeding or advancing motion may have to be included for the purpose of maintaining the desired contacting interfaces as the surface of the workpiece is machined away by the chemical milling
15 reaction. If the tool only works one surface of the workpiece, this "advancing" motion will have to be a linear motion whereby the workpiece and tool are slowly brought together so that each orbital contact between the tool and workpiece will be uniform despite the fact that
20 the workpiece surface is being machined away. If the tool orbits around an exterior or interior surface of the workpiece machining the circumference thereof, the "advancing" motion will have to be represented by a slow change in the radius of orbit to maintain the constant
25 contact between tool and workpiece as the circumference of the workpiece is machined away.

Reference to Figures 1 and 2 will illustrate a very simple embodiment of this invention which, in addition to a feeding motion, utilizes only an orbital contacting

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motion between the workpiece and tool. In this application, Figure 1 shows a schematic cross-sectional elevation illustrating a cylindrical workpiece (10) and tool (20) as engaged during the machining operation, while
5 Figure 2 shows a schematic cross-sectional plan view of the embodiment shown in Figure 1. In the embodiment illustrated, the metal workpiece (10), having a cylindrical surface configuration to be machined, is secured onto an orbital table (14), with the axis of
10 cylindrical workpiece (10) vertically disposed, and which moves the workpiece (10) in a circular, orbitally oscillating relationship with the motion being limited to the horizontal plane. It should be appreciated that the relative motion is orbital and not rotational. As in
15 conventional chemical milling, the tool and workpiece must be conductively connected to a DC power supply (not shown) with the tool (20) as cathode and the workpiece (10) as anode.

Tool (20), secured to platten (16), should be
20 fabricated, having a cylindrical opening (22) therethrough, the walls of which serve as the working surface. The cylindrical working surface of opening (22) is provided with a uniform layer of an abrasive particles (24) bonded to the tool. Techniques for bonding the
25 abrasive particles to the tool body are well known and need not be detailed here. The particle size of the abrasive (24) on the cylindrical surface of tool (20) should be relatively small; i.e., smaller than about 70 mesh, and ideally about 320 mesh. The surface density of

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the abrasive grit (22) should be reasonably high to assure that the passivation layer is completely removed during the short period of contact between the tool and workpiece.

5 During the processing, the relative orbital contacting motion as described, must be sufficient to cause the workpiece (10) to orbit about within tool (20), or vice versa, such that the abrasive particles (24) will lightly abrade the cylindrical surface (11) of workpiece
10 (10) with the area of contact continually changing; i.e., moving radially around both cylindrical surfaces (11) and (22). Specifically, at any given point in time, the area of contact will be a line, or very narrow band extending the full height of cylindrical surface (11) where the
15 working face (22) is tangent thereto, as depicted at the left side of workpiece (10) in Figures 1 and 2. As the orbit progresses, the line or band of contact will revolve around surface (11), so that one full orbital revolution will cause the entire cylindrical surface (11) to be
20 contacted by surface (22), and accordingly abraded.

 During the processing, a suitable chemical milling fluid (30) is admitted into the chamber between workpiece (10) and tool (20) via inlets (24), so that the chemical milling fluid will move downwardly through the chamber and
25 exit through the gap between tool (20) and orbital table (14), where it is recovered and reprocessed by any suitable means (not shown). Such chemical milling fluid processing and recirculation systems are well known in the prior art and need not be further described here. As

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shown in Figures 1 and 2, channels (18) can be provided within the upper surface of table (14) to facilitate the flow of chemical milling fluid from between the workpiece (10) and tool (20).

5 The chemical milling fluid (30), as noted, may be strongly passivating to the workpiece, so that the workpiece surfaces are quickly passivated to prevent and chemical milling machining thereof, were it not for the mechanical abrading action which prevents the build-up of
10 any passivation layer. As the abrasive particles abrade away a thin surface layer, including any formed oxides, to expose fresh non-oxidized workpiece metal, as a result of the motion of the contacting interface, the chemical milling reaction will cause metal to be removed at that
15 site. The continued relative motion will cause the abrasive particles to move away from the freshly abraded surface, so that the chemical milling machining thereof will continue. This action will progress around the cylindrical surface of workpiece (10) behind the
20 constantly moving area of direct contact. In view of the fact that a flow of the chemical milling fluid is caused by virtue of its being directed downwardly through the chamber between workpiece (10) and tool (20), the chemical milling fluid is caused to flow through the gap between
25 the tool and workpiece pursuant to conventional chemical milling practices. One of the unique features of this invention, however, is the fact that the workpiece and tool are caused to have a relative reciprocal motion so that the chemical milling fluid is further caused to be

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effectively "pumped" through the contacting gap between the tool and workpiece. It should be apparent therefore, that because of this added pumping action, there will be no pockets of chemical milling fluid which can be trapped
5 between the workpiece and tool surfaces which can adversely affect the processing. As a result, significantly higher metal removal rates can be utilized in the chemical milling processing, which will provide a smoother and more uniform finish to the chemical milling
10 machined surface.

In the above described embodiment, it should be noted that the flat upper surface (13) on workpiece (10) is not contacted or abraded by tool (20). Accordingly, this flat surface (13) will be very quickly passivated by chemical
15 milling fluid (30) so that virtually no portion thereof will be machined by either physical abrasion or the chemical milling reaction. As previously described, only the intersecting cylindrical surface (11) is machined, and because of this machining of just the one intersecting
20 surface, a very sharp intersecting right angle will be maintained between surfaces (11) and (13). Indeed, metal removal rates can be employed without any tendency for the chemical milling reaction to "round" or bevel away the sharp corner. While this is a rather simple example of
25 this particular beneficial feature of this invention, it does serve to illustrate an example of the macro controls available with this process. Specifically, without passivation of surface (13), this surface would be machined to some extent by the chemical milling reaction.

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This is because some metal removal would result from stray etching caused by chemical milling fluid passing between the cylindrical surface (22) of tool (20), and the flat upper surface (13) on workpiece (10), which would be manifested by a rounding of the angle of intersection between surfaces (11) and (13).

The parameters for the contacting orbital motion should ideally be the same as that used in orbital grinding. The gap between the body of tool (20) and workpiece (10) at their point of closest proximity will of course be equal to that distance the abrasive particles space the two components apart, and should be set to be the distance preferred for optimum chemical milling machineability. The maximum spacing between the tool (20) and workpiece (10) at their furthest apart position will be no more than the diameter of the orbit; i.e., typically no more than about 0.2 inch. As shown in Figures 1 and 2, however, that gap distance is exaggerated to facilitate an understanding of the figures.

Since the desired machining of the cylindrical surface of workpiece (10) will progressively reduce the radius thereof, the radius of the relative contacting orbital motion will have to be continuously increasing in order to effect an advancing motion so that the physical contact between the tool and workpiece will be maintained. The ability to effect this progressively increasing radius of orbit is available with appropriate commercial machine tool orbital tables through rather complicated linkage, which need not be described here. It is also within the

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skill of the art to be able to accurately calculate the machining rate and then preset the orbital table so that the radius of orbit will progressively increase as necessary to maintain the desired contact pressure between the tool and workpiece throughout the machining operation. The advance speed (rate) may be controlled as a function of the feedback of the contact force between the tool and the workpiece. As an alternative, and particularly towards the end of the machining action, it may be desirable in some situations to permit the contacting force between the tool and workpiece to be progressively increased so that the final machining action is limited primarily to a physical abrasion for the purpose of achieving a more precision finish.

In the above described embodiment, it can be seen that the relative contacting orbital motion will cause the tool to abrade the passivation layer from the surface of the workpiece, or prevent the formation of a passivation layer so that the surface can be machined by the chemical milling reaction between the fluid and workpiece immediately thereafter. During this entire operation, the tool is moving towards and then away from the workpiece, to effectively pump the chemical milling fluid through the gap to provide fresh chemical milling fluid. In this particular application the single contacting orbital motion will effect both requirements. Any curved surface such as cylindrical, hemispherical and the like can usually be machined by such a technique whereby a simple contacting orbital motion will effect both the desired

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machining operation as well as the chemical milling fluid pumping action.

Reference to Figures 3 and 4 will illustrate a rather different embodiment of this invention as may be utilized to abrade flat workpiece surfaces. In the case of such flat workpiece surfaces, a simple contacting orbital motion in the plane of the workpiece surface will not be sufficient to effect a reciprocating motion between the tool and workpiece as necessary to pump the through the interface gap. In such an application, therefore, it will be necessary to impose a relative reciprocal motion as well as a contacting orbital motion.

As shown in Figures 3 and 4, a workpiece (40), having an annular-shaped upper surface (42) with a frusto-conical portion (44) extending upward from the center, is machined by tool (50). Tool (50) has a flat bottom surface (52) with a frusto-conical recess (54) therein for mating with frusto-conical portion (44). The flat bottom surface (52), as well as the surface within frusto-conical recess (54) are both covered with an abrasive grit, as previously described. The workpiece (40) and tool (50) are attached to an orbital table and plate respectively, as previously described, and placed in a relative contacting orbital motion as also previously described. In addition to the relative contacting orbital motion, a relative reciprocal motion is also effected between workpiece (40) and tool (50) so that these two components repeatedly move together and touch for a period of time sufficient to lightly abrade the workpiece surface, and then move away from each

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other. Accordingly, Figure 3 illustrates that relative position during the cycle where the workpiece and tool are in contact, while Figure 4 illustrates the relative position when the two components are at their maximum
5 separated position.

As the abrasive grit on surface (52) comes into contact with surface (42) of workpiece (40), as shown in Figure 3, it should be apparent that the relative contacting orbital motion at the interface will cause the
10 abrasive grit to abrade surface (42) and remove any passivation layer therefrom, so that the chemical milling reaction will proceed to machine surface (42) immediately after the passivation layer is removed, and for a period of time while tool (50) is spaced away therefrom as a
15 result of the relative reciprocal movement. While surface (42) will start to become passivated thereafter, any surface oxidation that occurs will again be removed when the cycle is repeated, so that the chemical milling action can continue.

20 As before described, it will also be necessary to impose a feed motion to the reciprocating motion, so that with each cycle of reciprocation, the tool is brought down further than before so that it will continue to contact the workpiece surface (42), as that surface is
25 progressively machined to a lower position.

As for the surface of the frusto-conical extension (44), it will be machined in substantially the same manner as was the cylindrical wall of workpiece (10), in the previously described embodiment, with some notable

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distinctions. That is to say, if the surface being machined is only a flat surface, such as surface (42), the reciprocating motion cannot adversely affect its being machined as above described. It should be noted, however, 5 that the reciprocating movement can have a very significant effect on the machining action on surfaces that are not parallel to the contacting orbital motion, such as the sides of the frusto-conical extension (44). Specifically, if the contacting orbital and reciprocal 10 motions are synchronized in a one to one relationship, it can be seen that only one side of the frusto-conical extension (44) will be machined, since the tool (50) will move downward contacting only a portion of the frusto-conical surface at the same place with each reciprocation 15 movement, and then withdraw therefrom as the tool orbits to the other side. With a physical arrangement like this, therefore, in order to uniformly machine an entire circumferential surface when the tool is made to reciprocate therefrom, it is necessary that the contacting 20 orbital motion and reciprocating motion be synchronized so that all portions of surface are contacted and abraded at least over a number of reciprocating cycles. The preferred approach to achieve this assurance, is to abrade various differing portions of the curved surface during 25 successive contacting orbits so that the entire surface will be abraded within relatively few cycles of orbit. If passivation of the frusto-conical surface causes chemical milling machining thereof to be retarded, so that the chemical milling machining rate of the flat surface (42)

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proceeds at a much faster rate, it may be necessary to program the motion so that each pass of the abrasive tool over frusto-conical surface will necessarily affect a greater amount of mechanical abrading.

5 With further regard to the frusto-conical portion (44) of workpiece (40), it can be seen that the flat upper surface thereof would not be machined, as in the case of the top of cylindrical workpiece as described earlier. In this embodiment, however, the tool is progressively
10 working its way downward, so that eventually, if machining is continued long enough, there would be contact at the upper flat surface thereof.

In contrast to the above described embodiment as illustrated in Figures 1 and 2, the contacting orbital
15 motion in this embodiment will not cause the contacting surfaces (42) and (52) to reciprocate. This is because the plane of the contacting orbital motion is parallel to the plane being machined, at least with regard to surface (42). In this embodiment, therefore, it is necessary to
20 impose a separate relative reciprocating movement for the purpose of pumping the chemical milling fluid through the gap between surfaces (42) and (52) to prevent the chemical milling fluid from becoming over-heated or over-saturated with dissolved workpiece material. It should become
25 apparent, however, that if the plane of contacting orbital motion were not parallel to the surface being machined, but instead is inclined at an angle thereto, as depicted in Figure 5, then the single relative contacting orbital motion would effect a reciprocating relative motion or

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displacement, so that the tool and workpiece would come into contact at the low point of the orbit, to effect the essential physical abrasion to remove the passivation layer, and thereafter orbit away from a contacting relationship to effectively pump the chemical milling fluid as necessary to effect its circulation.

As shown in Figures 5 and 6, tool (60), having an axis of rotation as depicted thereabove; i.e., inclined at an angle to the surface to be machined, will come into contact with the upper surface of workpiece (62) at the furthest extent of downward-leftward orbital motion. Subsequently, as tool (60) orbits upward and to the right, it will move away from workpiece (62). Accordingly, a relative reciprocal motion will result from the contacting orbital motion. While the tool (60) will not be in contact with the workpiece (62) throughout the entire orbital motion, that makes little difference in this embodiment, as the entire surface (64) of workpiece (62) is in fact contacted and abraded by tool (60) while orbiting through its most downward position. In applications such as this, it is critically essential that the density of the abrasive grit on the tool surface be exceptionally high to assure that the entire workpiece surface is abraded during the quick pass-over by the tool.

As previously described, a means will have to be provided for feeding a chemical milling fluid into the gap between tool (60) and workpiece (62), which will readily be pumped out of the interface by the reciprocating motion between tool (60) and workpiece (62). In this embodiment

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it can clearly be seen that the contacting orbital motion for abrading the surface of workpiece (62) as well as the reciprocating motion for pumping the chemical milling fluid are effected by the one orbital motion. As in the case described for the embodiment of Figures 1 and 2, the orbital motion will have to be set to have a continually increasing radius of orbit in order to continue to maintain the essential contact as the surface of the workpiece is machined down, or in the alternative, a feeding motion can be imparted to a constant orbital motion to bring the tool and workpiece closer together as the workpiece is machined.

The above described embodiments have been limited to the machining of very simple surfaces merely for the purpose of describing the various forms of machining phenomenon that can be encountered in the practice of this invention. It should be apparent that those surfaces as described can be easily machined with other forms of conventional machining practices. Therefore, the process of this invention will find much better utility in the machining of more complex configurations which are not easily machined by other techniques. For example, the machining of an image in a coin or die or other multifaceted surfaces are one type of example where this process would find particular utility, as well as the machining of complex three-dimensional and curved surfaces such as the surfaces of turbine blades and the like which are very difficult to machine by other processes, but can easily and very effectively be machined individually or in

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groups or even an entire arrangement thereof on a turbine wheel by the process of this invention.

Reference to Figures 7 and 8 will illustrate an example of the machining of a multifaceted workpiece, where Figure 7 is a schematic cross-sectional view of the blank workpiece (70), while Figure 8 illustrates the workpiece (70) and tool (72) in contact near the conclusion of the machining operation. As can be seen in Figure 7, workpiece (70) has a nonuniform cross-section having a hole (74) in the upper surface. Two small narrow holes (76) are provided through the workpiece (70) for admitting the chemical milling fluid during the chemical milling machining.

Figure 8 schematically illustrates the machining of workpiece (70) in accordance with this invention, where tool (72) is made to orbitally contact the upper surface of workpiece (70) during the chemical milling machining process. In this embodiment, the axis of orbital rotation is perpendicular to the upper flat surface of the workpiece, so that there will be no reciprocal vertical displacement as a result of the contacting orbital motion. As can be seen in Figure 8, a frusto-conical stem portion (78) on tool (70), extending vertically downward, will serve to machine out hole (74) providing it with a tapered side interior surface, at least to the extent machined. An annular space (80), surrounding stem (78) will serve to form an annular neck around hole (74). The upper flat surface (82) around hole (74), as well as the inclined surface (84) at points (84a) and (84b), will not be

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machined as they are not contacted by tool (72), and will therefore be passivated by the chemical milling fluid to be unaffected by the chemical milling reaction. To the extent that there are flat horizontal surfaces being machined in this application, it will be necessary to impose a relative reciprocal motion between workpiece (70) and tool (72) for the purpose of pumping chemical milling fluid through any such horizontal interfaces, as previously described. As can be seen from this embodiment, the process can be used to machine a plurality of differing surfaces by utilizing a three-dimensional tool which is a negative complimentary image of the workpiece surfaces to be effected by the machining operation. The negative image imposed into the tool will have to be slightly undersized and oversized to compensate for the orbital displacement as the orbital path of the tool image will define the image machined.

In the process of this invention the workpiece is passivated until such time as it is abraded by the tool surface, the process variables are significantly reduced so that the image created in the tool face, as corrected for its contacting orbital motion, is essentially the same as that machined into the workpiece, with little if any requirement for any trial and error testing. As an example thereof in the above described embodiment, those surfaces (82) and (84a) and (84b), remaining untouched by the tool (72), will not at all be affected by the chemical milling reaction because of the macro controls afforded by this process. In conventional chemical milling

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processing, however, these surfaces would have some metal removed therefrom by the chemical milling reaction. For example, the cylindrical surface of hole (74) will be completely unaffected by this process, while in
5 conventional chemical milling, at least the upper portions thereof would have some metal removed therefrom as the result of stray etching between that upper cylindrical surface (86) of hole (74).

Another of the unique advantages of this invention is
10 illustrated with reference to the machining of hole (90); i.e., surface (92). As is apparent from Figure 1, hole (90) is entirely formed by the machining action of flange (94) on tool (72). As the hole depth is machined downward by the lower face of flange (94), the side of the hole;
15 i.e., surface (92) is suitably machined and dressed by the side surfaces of flange (94) for a short time only. Once the flange (94) has progressed below any given point on the cylindrical side surface of hole (90) it has just formed, the abrasive action of flange (94) of course
20 ceases, and that portion of surface (92) is quickly passivated by the chemical milling fluid thereby preventing further machining. The passivation layer on surface (92) will prevent any metal removal therefrom, thus preventing any overcutting as is otherwise common in
25 conventional chemical milling.

Reference to Figures 9a, 9b, 9c, and 10 will illustrate still another embodiment of this invention which is utilized to machine a repaired metal part, such as a turbine blade as illustrated. For example, turbine

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blades having flaws therein, such as holes or cracks can be easily repaired by cutting out the flaw and depositing new metal in the cut-out area. This procedure is illustrated in Figures 9a, 9b, and 9c. Here a crack in the turbine blade (100), as shown in Figure 9a, is cut out by any suitable means, typically by electrical discharge machining or grinding. This renders the turbine blade with a cut-out as shown in Figure 9b. Thereafter, new metal is deposited into the cut out portion by "dabber welding". To assure that the fill metal is as high as will be necessary for properly machining the turbine blade, it will of course be necessary to overfill the cut out as shown in Figure 9c. Finally, the new metal should be machined down to recreate the original contour.

Pursuant to prior art practices, this machining step is where the difficulty arose. For example, the contour sought to be machined in this particular application is not flat or circular, so that conventional machining could not be utilized. Conventional chemical milling would not have been appropriate because material removal would occur on all portions of the turbine blade surface, so that the original contour could not be restored.

The process of this invention, however, is ideally suited to the machining of such a repaired turbine blade, as schematically illustrated in Figure 10. As generally shown in Figure 10, and more specifically illustrated in Figure 11, the partially repaired turbine blade (100) is made the workpiece, while tool (102) is made an orbital chemical milling machining tool as taught herein.

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Pursuant to the above description, the strongly passivating chemical milling fluid will passivate the entire surface of the turbine blade workpiece, including the new filled metal (104). In this application, however, 5 the orbiting tool (102) will contact only the protruding filled metal (104), and accordingly, only that protruding filled metal (104) will be chemical milling machined pursuant to the principles described above. The original turbine blade material, already having a contour as 10 desired, will remain passivated throughout the entire operation, and will thus retain its original desired contour. In this application, however, where the contacting orbital motion of the tool (102) does not orbitally move away from the filler metal (104), it will 15 be necessary to provide an oscillating, reciprocal movement between the tool (102) and the filler metal (104) for the purpose of increasing the circulation of chemical milling fluid between the tool and workpiece. In this embodiment, the reciprocal motion will serve the added 20 purpose of abrading both sides of the turbine blade where material (104) is on both sides of the blade as shown in Figure 11.

In addition to repairing defective turbine blades having filler metal therein, the above described process 25 can also be utilized to correct the contour of turbine blades, or any other such metal part which may be defective by virtue of the fact that the contour is not as exact as desired. Utilizing an application as illustrated in Figure 11, the process of this invention can be

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utilized to abrade any high spots on the metal workpiece surface.

Of significantly more importance, however, is the fact that the process of this invention can be utilized to simultaneously machine a group of turbine blades including a whole circle of turbine blades already affixed to a turbine wheel, whether mechanically attached thereto or formed as a one piece turbine wheel. As previously noted, the machining of the one piece turbine wheel has proven to be a very difficult operation. As schematically shown in Figure 12, however, all the turbine blades on a turbine wheel can be machined simultaneously in an embodiment as shown, where the tool (110) comprises an upper portion (112) and lower portion (114), fitted together over a plurality of turbine blades (116). Utilizing the same principle as described above for abrading a single turbine blade, the plurality of turbine blades (114) can be abraded and machined simultaneously to effect exacting dimensions and contour to each of the turbine blades in one single operation.

In operation, the chemical milling fluid should be selected which is strongly passivating to the workpiece metal, with the degree of passivation depending upon the nature of the machining to be performed; i.e., whether macro or micro controls are to be performed. In the embodiment illustrated in Figure 1 for example, the passivating nature of the a chemical milling fluid serves only to effect a macro control of the chemical milling machining action, that is to completely prevent machining

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on certain selected surfaces. Therefore, the rate of passivation is not of any particular significance during the machining operation.

It should be noted that passivation is dependent upon many variables, namely, the chemical milling fluid itself, the workpiece metal, the chemical milling fluid pH, concentration and temperature, and flow rate. Therefore, it is not possible to define a given chemical milling fluid which will have suitable passivation characteristics for all applications.

In very general terms, when the workpiece is steel, a suitable chemical milling solution would be ferric chloride. When titanium is to be milled, hydrofluoric acid will be employed. Aluminum is ordinarily milled with sodium hydroxide. In equally general terms, the steps ordinarily taken and the auxiliary ingredients normally added to minimize passivation are to be avoided, contrary to the usual practice and expectations in the art.

At the same time it is also possible in many circumstances to eliminate the normal requirements of masking the surfaces of the workpiece in areas not to be milled. The formation of the passivation layer will be sufficient to protect the surface conformation. The thin passivation layer may be removed when processing is complete if desired although in many circumstances it may be left in place.

In light of the avoidance of steps taken to prevent passivation, the overall rate of chemical action will often be more rapid in the present invention. In

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addition, the active physical removal of the passivation layer by the orbital grinding operation will accelerate the overall process.

5 Unless specifically desired and provided for, there will ordinarily be no undercutting formed by the procedure in the present invention.

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CLAIMS

What is claimed is:

1. A method of chemical milling a a shape into the surface of a workpiece, characterized by the steps comprising forming a tool comprising a body with a surface of abrasive particles complementary to the intended shape of said workpiece and mounted in an oscillating relationship opposed to the workpiece surface to be machined; introducing a chemical milling fluid between the tool and the workpiece and forming a passivation layer on the surface of the workpiece; causing a relative contacting motion between said tool and said workpiece such that said abrasive particles on the surface of said tool will abrade said workpiece only on those areas of the workpiece where machining is to be performed and thereby selectively abrade away only selected portions of said passivation layer on said workpiece to expose fresh workpiece metal thereunder, removing a select potion of the workpiece surface by chemical milling and reforming the passivation layer while causing a relative reciprocal motion between the tool and the workpiece sufficient to pump the chemical milling fluid between the tool and the workpiece while advancing the tool to maintain working contact between the tool and the workpiece.

2. A method according to claim 1 wherein the relative orbital motion is in a plane corresponding to the surface to be machined so that the reciprocal motion is independent of, and in a plane different than, the relative orbital motion.

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3. A method according to claim 1 wherein the workpiece has at least two surfaces to be machined and the tool has at least two surfaces having abrasive particles so that at least two corresponding surfaces of the workpiece are machined simultaneously.

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4. A method according to claim 1 in which the workpiece is one or more turbine blades, and the tool has a form to fit around the turbine blades and machine compound shapes.

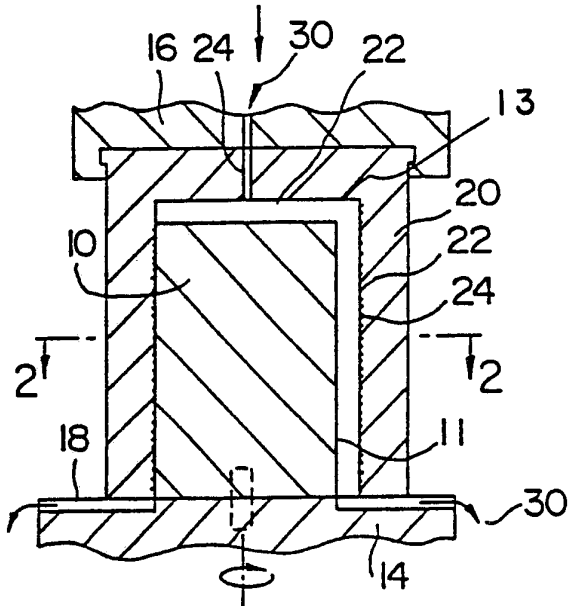


FIG. 1

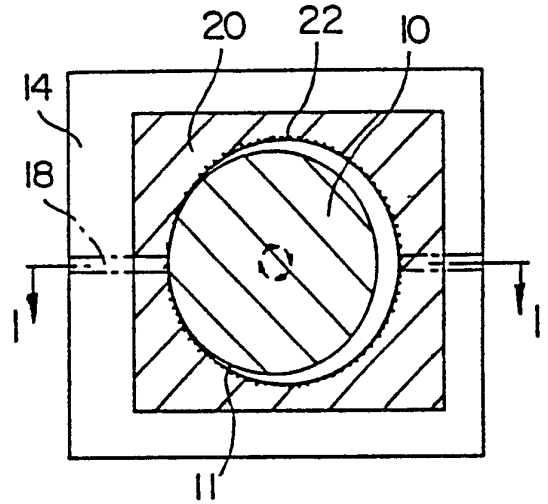


FIG. 2

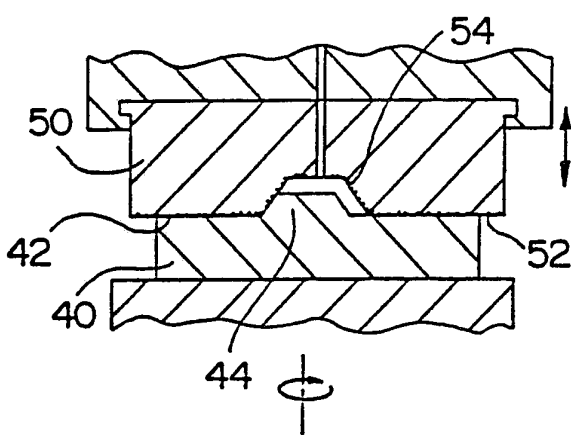


FIG. 3

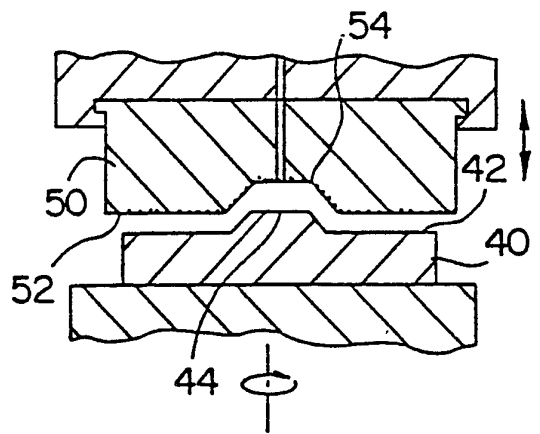


FIG. 4

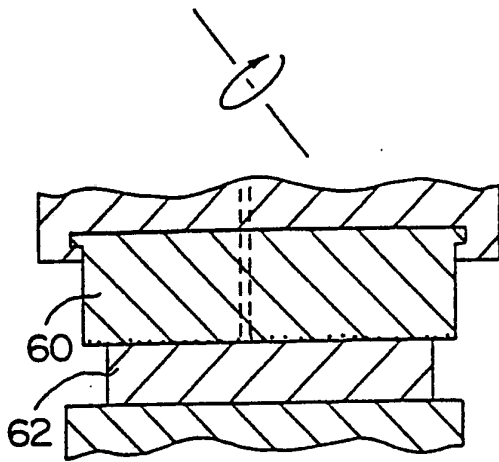


FIG. 5

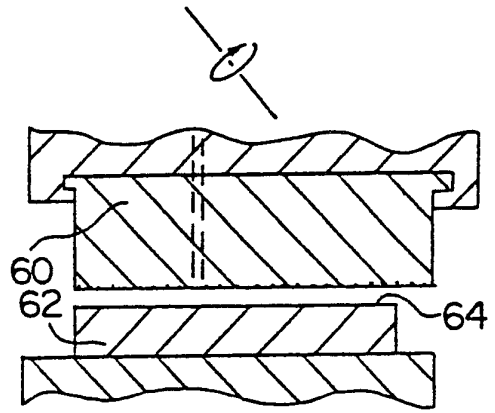


FIG. 6

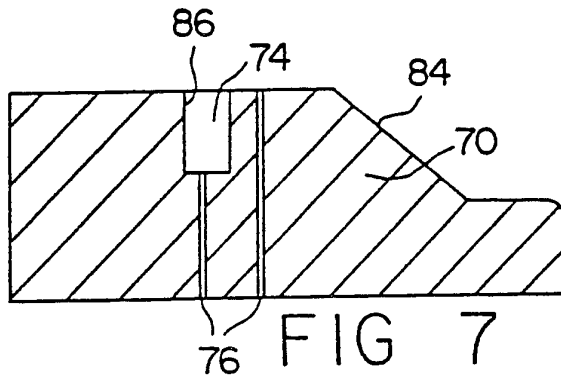


FIG. 7

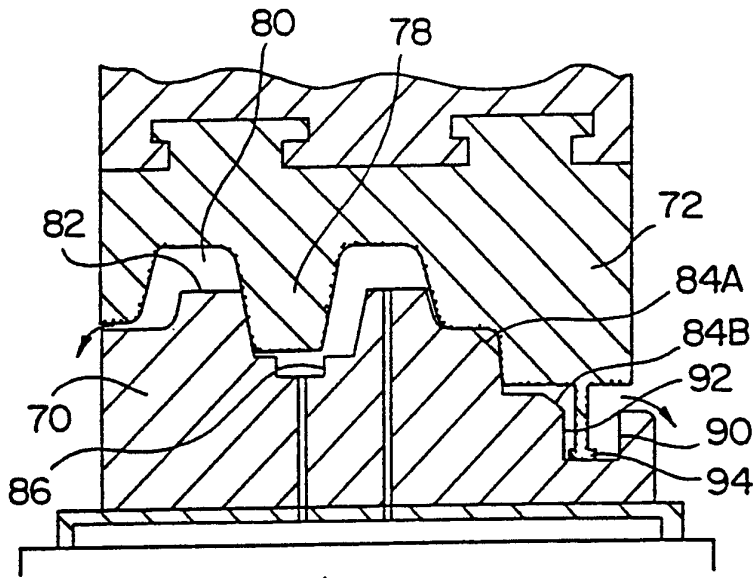
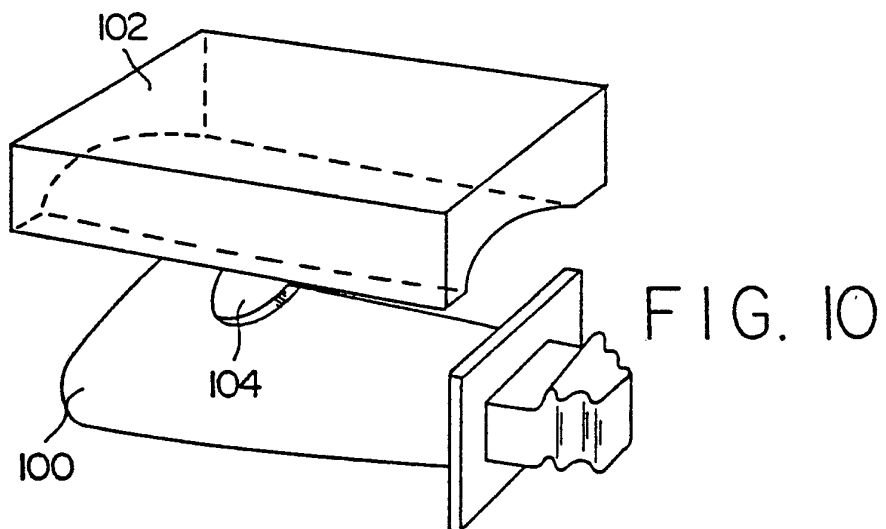
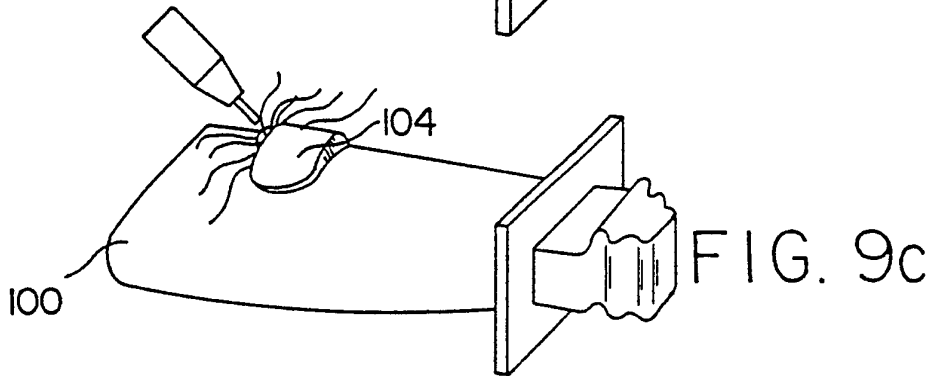
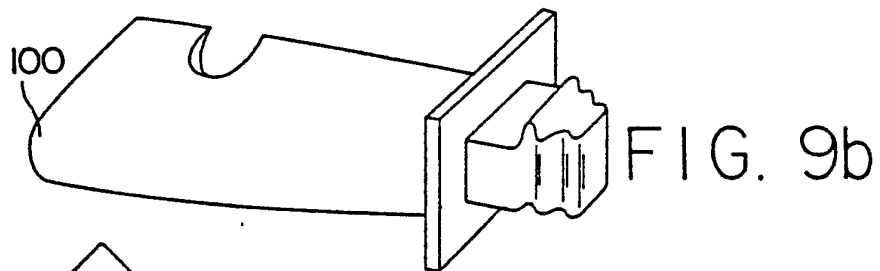
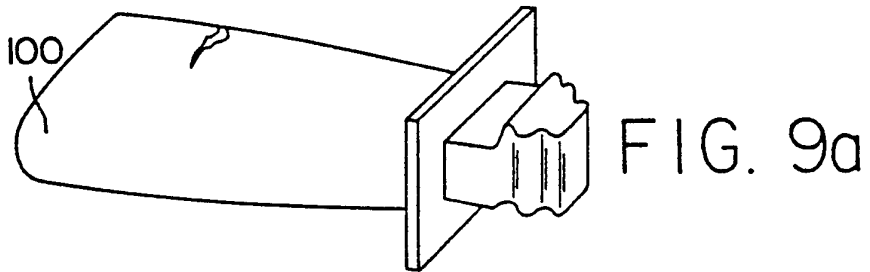


FIG. 8



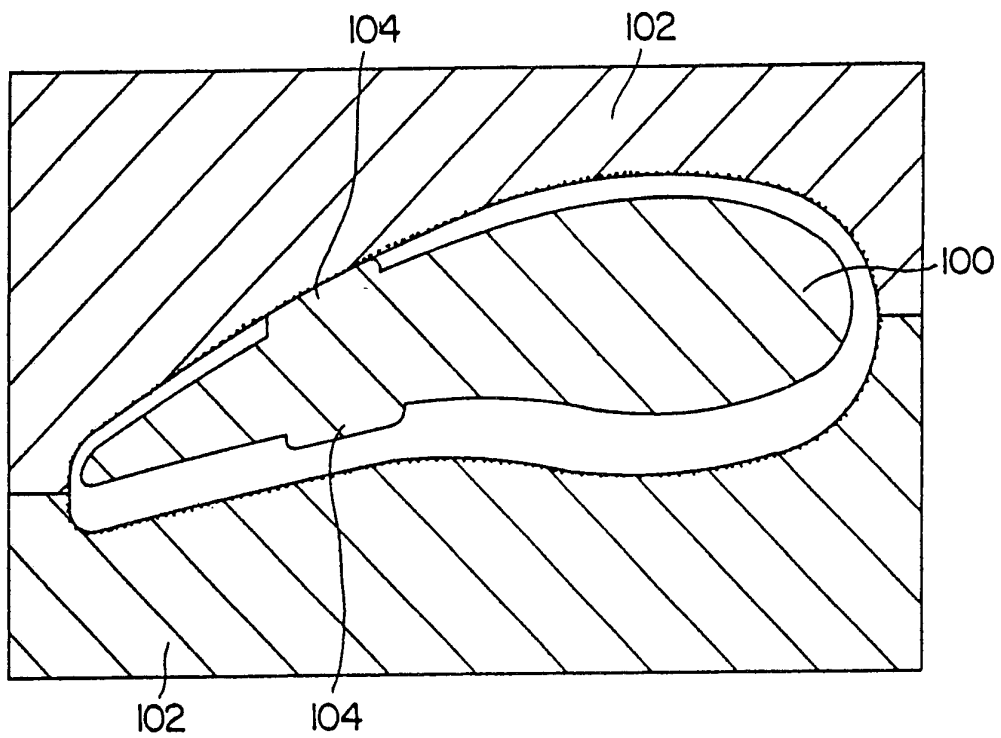


FIG. 11

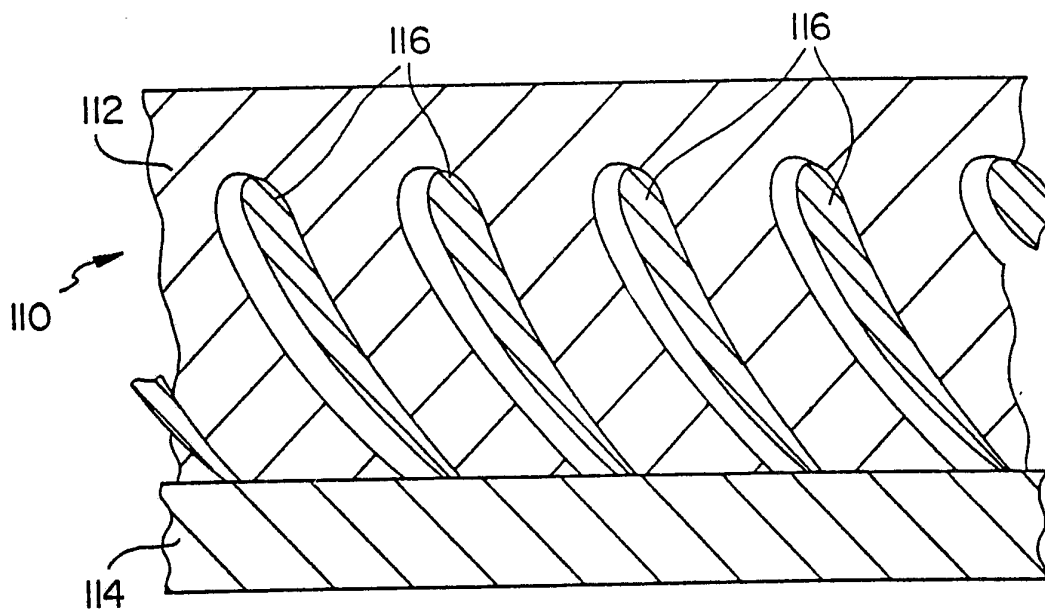


FIG. 12

INTERNATIONAL SEARCH REPORT

PCT/US92/09668

A. CLASSIFICATION OF SUBJECT MATTER

IPC(S) :C23F 1/04

US CL :156/645, 661.1

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 204/129.46

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

APS - Chemical Milling, Oscillating, Orbital, Reciprical, Abrasive

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US, A, 4,113,549 (Brimm) 12 September 1978, See column 3, lines 49-68.	1-2
A	US, A, 4,070,752 (Robinson) 31 January 1978, See column 5, lines 16-40.	1
A	US, A, 4,585,519 (Jaffe et al.) 29 April 1986, See column 6, lines 11-15.	1
A	US, A, 4,215,194 (Shepherd) 29 July 1980, See column 4, lines 24-46.	1
A, P	US, A, 5,085,747 (Nikano) 04 February 1992, See column 3, lines 19-44.	1

Further documents are listed in the continuation of Box C. See patent family annex.

* Special categories of cited documents:	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A" document defining the general state of the art which is not considered to be part of particular relevance	"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"E" earlier document published on or after the international filing date	"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"&" document member of the same patent family
"O" document referring to an oral disclosure, use, exhibition or other means	
"P" document published prior to the international filing date but later than the priority date claimed	

Date of the actual completion of the international search

15 JANUARY 1993

Date of mailing of the international search report

22 FEB 1993

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INTERNATIONAL SEARCH REPORT

International application No.
PCT/US92/09668

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US, A, 3,816,273 (Snyder) 11 June 1974, See column 2, lines 34-43.	1
A	US, A, 2,933,437 (Loosme) 19 April 1960, See column 3, lines 30-60.	1